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Uncovering attitudes towards carbon capture storage and utilization technologies in Germany: Insights into affective-cognitive evaluations of benefits and risks

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ABSTRACT

Carbon capture and storage (CCS) and carbon capture and utilization (CCU) are technologies which aim at mitigating climate change and saving fossil resources: CO_2 emissions from industrial plants are captured and stored underground (CCS) or used for the manufacturing of products (CCU). In contrast to CCS, CCU is less about the reduction of CO_2 emissions, since the global demand for feedstock CO_2 to be used for CCU products is considerably lower than the CO_2 emissions produced worldwide. Moreover, the CO_2 is only temporarily stored until the disposal of the CCU products. Instead, a reduction of fossil resources in product manufacturing is the primary goal for CCU. The successful roll-out of CCS and CCU is not solely determined by technical feasibility but also depends on public acceptance. Research has shown that acceptance of energy technologies is impacted by laypersons' attitudes. So far, little is known about differences in affective and cognitive evaluations of CCU in comparison to CCS. To address this research gap, an online survey was conducted in Germany (n = 449), in which affective and cognitive evaluation profiles for CCS and CCU were compared. Also, it was explored whether attitudes towards CCS are predictive of CCU acceptance. Results revealed basically similar evaluation profiles for CCS and CCU but CCU was rated significantly more positively. Comparing results for CCS supporters and opponents, it was found that CCS supporters rated CCU similarly positive whereas CCS opponents evaluated CCU significantly better than CCS. The findings can be used for communication concepts tailored to laypeople's requirements and concerns and yield implications for industrial policy-making.

1. Introduction

Climate change and the limited availability of fossil resources are two of the global challenges we are confronted with today, e.g., in the sectors of mobility, energy supply and use, and industrial production [1,2]. To achieve the global goal of limiting global warming to below 2 °C and to reduce fossil resource depletion, the increased use of low-carbon technologies, e.g., renewable energy technologies, energy efficiency measures, electric mobility, and carbon capture and storage (CCS), in these sectors is required [2–6]. Another technological approach to address these ecological challenges is carbon capture and utilization (CCU), which shares some similarities with the CCS technology, but there are also some important differences [7]. CCS is seen as a solution which can contribute to climate change mitigation by capturing CO_2 emissions from industrial plants and permanently storing them underground instead of releasing them into the atmosphere [6,8]. However, CCS cannot account for all CO_2 emissions from industrial sources, since capacities for on-shore storage are limited in Germany (see Section 2.1). In comparison, the process route for CCU differs: CO_2 from industrial processes is also captured but instead of being stored it is used as a renewable carbon feedstock for the production of commercial products, e.g., plastic products or CO_2-based fuels [9,10]. Accordingly, CCU is regarded as more effective in saving fossil resources than in reducing greenhouse gas emissions because the CO_2 demand for the CO_2-based products is much lower than the amount of global carbon dioxide emissions [9,11].

Research and past experiences have shown that the acceptance of CCS in Germany and other parts of Europe is rather low and pilot projects have been met with considerable opposition, occasionally leading to cancellations of projects [12–15]. Novel CCU technologies such as the CO_2-based production of fuels and plastic products are still at an early stage of implementation with first industrial production plants being in operation (e.g., [16]). Therefore, it is still not sufficiently understood whether the public accepts CCU technologies and

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products and which factors influence the approval or rejection of the CCU products and the infrastructure required for the manufacturing of CCU products (production sites and also possibly required CO_2 transport infrastructure, e.g., pipelines). It is known from technology acceptance research in a variety of contexts (including CCS and renewable energy technologies) that benefits and risks associated with a technology are inversely related and considerably affect acceptance [17–19]. Often, when people do not feel well informed about a novel technology, they rather base their judgements of benefits and risks on affective evaluations than on cognitive evaluations [20–23]. As previous studies revealed a rather low awareness of both CCS and CCU technologies [24–27], an understanding of the relevance of affective responses and beliefs for the acceptance of CO_2-based technologies is highly valuable.

Therefore, our research aim was to comparatively study the impact of affective responses and beliefs on CCS and CCU acceptance in Germany to unveil if the same or different parameters are acceptance-relevant in the CCS and CCU context. It was investigated whether laypeople distinguish between the two technological concepts and if attitudes towards CCS are predictive of CCU acceptance. Past research has revealed that perceptions of energy technologies in general and of CCS and CCU in particular are not only impacted by technology-related factors but also by person-related factors (individual differences in laypeople). These person-related factors can include socio-demographic characteristics (e.g., age or gender) but also previous knowledge and experience with the technology or even personality characteristics (e.g., one's general attitude towards technology) [18,26–29]. The obtained insights into hidden drivers and barriers of CCS and CCU acceptance can inform the development of communication concepts that match information requirements and concerns of different user groups.

The study focus on Germany was chosen because CCU is highly topical in Germany: There is a variety of research and development programs on CCU [30,31] and first industrial developments of plastic products and fuels made partly from CO_2 have emerged in recent years (e.g., [16,32]). On the contrary, CCS pilot projects in Germany have been ceased and future prospects for CCS within the next years have been assessed as low [31,33]. Two of the key factors for the bleak future for large-scale CCS projects in Germany have been political controversies around the implementation of CCS and a lack of public acceptance [15,31,33]. Resistance to technology infrastructure such as large-scale CCS facilities is a complex issue, in which a number of social, psychological, and contextual factors is involved [14]. As reasons for the low level of acceptance for CCS in Germany research has identified (among others) perceived risks for human health and the environment, especially linked to the process step of CO_2 storage, and low perceived benefits for the host community of the storage site [14,15,34–36]. Other factors, which have been found to decrease the acceptance of CCS projects, are a lack of trust in operators and in the information on the project they provide to the public, as well as perceived non-transparent decision strategies [14,31,35]. Also, opposition against CCS projects organized by stakeholders such as non-governmental organizations (NGOs), politicians, local councils, and local citizen groups has been revealed to play a role [14].

2. CCS and CCU – technology and public perception

2.1. CCS and CCU in the light of climate change – technology and aims

As a technological solution aimed at climate change mitigation, CCS has been researched and industrially implemented since the 1980s [7,27]. Until recently, CCS has received more public attention than carbon capture and utilization technologies [7,9]. From a technological point of view, CCS and CCU share the process step of CO_2 capture. CO_2 can be captured either from the atmosphere (air capture) or from point sources (flue gas from industrial sources such as power plants, oil refineries, or chemical plants) [9,11]. Flue gas from point sources features a high purity of CO_2 and therefore requires less additional energy for CO_2 capture compared to atmospheric CO_2 (as the CO_2 concentration in the ambient air is much lower). This makes CO_2 capture from point sources more efficient in reducing emissions and thus from a technical perspective preferable to air capture [11]. Aside from CO_2 capture, the subsequent pathway of CO_2 differs and aims at different ecological goals for CCS and CCU: In the CCS process, the captured CO_2 is transported (by ship, truck, or pipeline) to a geological or ocean storage site (e.g., depleted oil fields, deep saline aquifers, or the ocean floor), where it is permanently stored [7–9]. By storing the otherwise released CO_2 emissions, CCS is seen as a strategy for climate change mitigation [7]. For CCS, the net benefit in CO_2 emission reductions does not equal the amount of CO_2 captured but is somewhat lower because the CCS process requires energy (referred to as "energy penalty" [37]) and energy generation produces additional CO_2 emissions [38]. It is estimated that CCS in combination with BECCS (bioenergy with carbon capture and storage) can help to lower worldwide CO_2 emissions by 25% till 2100 and it is regarded as the most important individual action for cutting the amount of CO_2 emissions [7,39,40]. If a power plant is equipped with a CCS system, it is estimated that the CO_2 emissions from the plant can be cut by 80–90% [8]. But onshore CO_2 storage capacities in Germany are limited, covering only a small number of "power plant generations" [7].

In contrast, CCU technologies have a limited potential for reducing CO_2 emissions and are regarded as more effective in reducing fossil resource use, as the process route for CCU deviates from CCS: Instead of storing the captured CO_2, it is used as a renewable feedstock in the manufacturing of a variety of products [9,11].

There is a multitude of carbon utilization options: CO_2 can either be directly used (e.g., for the carbonation of beverages) or converted into chemicals and fuels [9,41]. Since CCU technologies are numerous and diverse, the stages of implementation vary greatly. In contrast to well-established CCU options such as enhanced oil recovery, methanol and urea production, novel CCU technologies such as the CO_2-based production of fuels and plastic products are still at an early development stage [10,26]. In the manufacturing of fuels and plastic products, the captured CO_2 can be used as renewable carbon feedstock replacing a part of the commonly required fossil feedstocks [10]. The first products have become commercially available on the market, such as polyols by Covestro [16], which are used as intermediate products for the manufacture of, for example, foam mattresses, and synthetic fuels by Audi [32]. Partly substituting the required fossil resources by CO_2 (e.g., 20 wt% CO_2) can account for a reduction of 13–16% in fossil resource consumption and 11–19% in GHG emissions related to conventional polyol production processes [10]. In the CCU context, the captured CO_2 is only temporarily stored in the manufactured products until the combustion (in the case of fuels) or disposal (in the case of commodities) of the product [7,9,40].

The role that CCU plays for environmental protection is still not fully understood (since discussions often only focus on CO_2 emission reductions and climate protection [40]). Not every CCU technology is equally ecologically beneficial. That is why every technology has to be evaluated individually by a holistic life cycle approach analyzing a number of environmental effects, among others: fossil resource depletion, global warming impact, eutrophication, acidification [10]. In a life cycle analysis, these environmental impacts are considered for the whole "CCU product life cycle" covering all process steps involved: CO_2 capture and transport, the manufacturing of CCU products at the production facility, the usage of CCU products by consumers, and finally the disposal stage. An important prerequisite for a low carbon footprint of CCU is that the required energy is supplied by renewable sources. The use of coal for CCS and CCU would be a front-end problem because worldwide energy generation from fossil sources accounts for more than 40% of the global CO_2 emissions [7].

Recent research [40] suggests to treat and discuss each technology individually to account for the differences in the ecological motives of

CCS and CCU and to avoid a commingling of the two technological concepts in the public discourse that may lead to misconceptions about the ecological motivation of CCU technologies (e.g., CCU being evaluated only in light of its climate mitigation potential). But it is still unclear whether laypeople distinguish between the two CO_2-based technologies in their judgements, i.e., whether CCS and CCU are evaluated similarly or individually.

2.2. Public acceptance of CCS and CCU

The successful roll-out of the CCS and CCU technologies depends on the public acceptance of the necessary infrastructure parts for carbon capture and storage respectively utilization, in conjunction with a positive adoption of the CO_2-derived products on the market. In research literature, public acceptance is a multi-faceted concept that is differently defined and understood according to the context it is used in. In the energy technology acceptance framework of Huijts et al. [18], acceptance is defined as a behavioral response that supports the implementation of a technology in contrast to impeding it. However, Batel et al. [42] understand energy technology acceptance as a passive tolerance of energy infrastructure, which does not automatically imply people being in active support of the project. In this research paper, we understand CCS and CCU acceptance as Huijts et al. [18] define it: a positive attitude to or approval of CCS and CCU technologies.

Experiences from past energy infrastructure projects have shown that the implementation of large-scale energy technologies, e.g., renewable energy production facilities, transmission lines, and district heating, often faces considerable opposition by residents [43–45]. Especially in the CCS context, a lack of public acceptance has led to the delay and even cancellation of (pilot) CO_2 storage projects in Germany and other European countries [12–15]. With novel CCU technologies such as the CO_2-based production of fuels and plastic products being in an early stage of implementation, it is not clear if the utilization options and products made partly from CO_2 are accepted by the public and, if so, which factors play a role for CCU acceptance.

In the context of CCS and CCU technologies, different levels of acceptance are affected. CCS as a large-scale infrastructure technology requires socio-political acceptance (general acceptance of CCS and policies for CCS by the public, politicians, and relevant stakeholders) and citizen or community acceptance of residents living near (proposed) storage sites [18,46]. In contrast, CCU can be regarded as both: an infrastructure technology (requiring infrastructure elements for CO_2 capture, transport, and manufacturing of the CO_2-based products, e.g., production sites and possibly pipelines needed for CO_2 transport) and a product technology (since the outcome of CCU processes are commercial products, in which fossil resources are replaced by CO_2 as renewable feedstock). Thus, a successful roll-out of CCU depends not only on the socio-political acceptance of CCU technologies and the community acceptance of (proposed) production sites but, on top of that, on a positive market adoption of CO_2-derived products, denoted as market or consumer acceptance [18,46].

According to the technology acceptance framework by Huijts et al. [18], the acceptance of sustainable energy technologies (i.e., technological approaches to address environmental and societal issues of energy consumption,[1] such as renewable energies, hydrogen technologies, and CCS) is impacted by a set of influential factors related to the technology itself, the planning and implementation process, and person-specific characteristics. Technology-related factors identified in the framework are the benefits, risks, and costs of the technology perceived by laypeople. In close connection to cognitions, it is also important how people feel about a technology (positive or negative affective responses). Beside judgements of the technology, perceptions of the planning and implementation process can considerably affect project acceptance: e.g., trust in involved actors, perceived fairness of the siting process, and perceived equity of the distribution of benefits and risks. The acceptance model of Huijts et al. [18] also takes account of individual differences in laypeople: it includes experience and knowledge as factors influencing the attitude towards an energy technology.

While issues of acceptance have been extensively studied in the CCS context (for an overview of studies see L'Orange Seigo et al. [48]), CCU technologies have only recently gained attention in acceptance research (first studies arised 2014, for an overview of studies see Jones et al. [49]). Nevertheless, previous studies in both technology contexts have found support for the relevance of perceived benefits and risks for acceptance [25,27,34]. In the CCS context, a variety of associated risks have been identified: among others, CO_2 leakage into the atmosphere during CO_2 transport and storage [35,50] (possibly in the form of sudden explosions or related to health effects [48]), earthquakes [51,52], and groundwater pollution through saltwater from saline aquifers [35,50]. Risk perceptions of the CCS technology also referred to the dimensions of unknown and uncontrollable risks. Past studies have revealed safety concerns and fears of unknown and unforeseen risks due to beliefs that the CCS technology was still technologically immature and that scientists were unable to judge the risks appropriately [19,35,50]. Moreover, the process steps of CO_2 transport and storage were perceived to be difficult to control and there were public concerns of long-time storage effects [35,52]. Huijts et al. [24] examined perceived risks for different risk targets (society, environment, own person, and one's offspring) and found that concerns for the environment and one's offspring were highest. Perceived risks outweighed perceived benefits of CCS in this study. Identified benefits associated with CCS mainly concerned economic topics: job creation and business opportunities [50]. Also, ecological benefits in terms of climate mitigation were identified but CCS was sometimes seen as competing against the roll-out of renewable energy technologies [48,53].

In the CCU context, perceived benefits and risks were identified in concrete terms for the CCU product level. A recent study [27] identified perceived risks concerning the product quality of CO_2-based products compared to conventional products (e.g., CCU products being less durable and comfortable) and sustainability concerns, i.e., the CCU technology was believed to be less sustainable compared to other low carbon technologies. Mixed results were found for environmental and health risks: Although environmental and health effects were rather not associated with CCU products in this study [27], they played a role in a qualitative study [54] and were attributed to a CO_2-release during product use and disposal. Moreover, studies on both CCS and CCU acceptance revealed that CO_2 itself was sometimes seen as a toxic substance that was believed to be explosive and harmful to health [35,36,54]. Perceived benefits of CCU products referred to environmental advantages that laypeople attributed mainly to binding CO_2 in the CCU products and thereby reducing the amount of global emissions. Reductions in fossil resource depletion were rather not acknowledged [54].

Besides that, first studies have recently looked into benefit and risk perceptions of CCU production plants. For CCU sites, perceived risks and drawbacks identified in a study by Perdan et al. [26] also referred to environmental and health concerns, to a possible CO_2 leakage from the production site, and to safety risks associated with CO_2 transport. However, less than half of those survey respondents, who reported to be worried about CCU, were afraid of these specific risks. Benefits associated most frequently with a CCU production plant were environmental and economic advantages: The amelioration of local air quality and the creation of jobs were recognized by more than half of those participants who believed that CCU would be generally advantageous to them.

[1] Sustainability should not only be evaluated in the light of ecological and economic outcomes but also in the light of the innovation process itself: a sustainable innovation also means that it is reached by a democratic process that enables citizen participation [47].

Overall, acceptance of the CCU technology and products was found to be positive with risk perception being rather low and the CCU technology and products being perceived as rather useful and beneficial [27].

2.3. Affect heuristics in risk perceptions and acceptance studies

Psychological research on emotions and cognitions has shown that individual mindsets and beliefs consist of affective and cognitive components (e.g., [55,56]). It has been found that energy technology acceptance is influenced by a strong interplay of affective and cognitive evaluations [18,57–60] – with laypeople often resorting to affective responses to assess benefits and risks of a technology [17], especially when they are not (respectively do not feel) knowledgeable about a novel technology [20–23]. The close interplay between cognitive components and affective responses was recently shown by Huijts [59] for the case of hydrogen fuel stations, revealing that cognitive evaluations (e.g., perceived fairness, prior awareness, novelty) can explain emotions (such as joy, anger, fear) and vice versa. From this work, it can be followed that measuring these cognitive-affective evaluations might inform policy makers and industry managers to steer reasonable energy projects.

In line with Peters and Slovic [61], in this study we define affective attitudes as "*holistic* reactions to objects or responses derived from spontaneous *images* of the objects" (p. 300). Whenever laypeople have a favorable general evaluative attitude towards a technology (positive bias), they tend to judge them high in benefits and low in risks. On the other hand, a negative overall attitude to the technology (negative bias) may result in high perceived risks and low perceived benefits [17]. The reliance on affective feelings in benefit and risk evaluations is known as "affect heuristic" [62].

Since benefit and risk perceptions were identified as crucial parameters affecting acceptance of energy and sustainable technologies (including CCS and renewable energy technologies) and past studies found public awareness of CCS and CCU to be relatively low [17–19,24–27], insights into the impact of affective responses and beliefs on CCS and CCU acceptance are of vital importance.

Findings from previous studies on CCS acceptance lend support to the relevance of affective responses for the public perception and acceptance of CCS. Midden and Huijts [20] identified affect as influence factor for perceived risks and benefits and findings from Huijts et al. [24] revealed that negative affect against CCS was slightly higher than positive affect: The most prevalent emotion evoked by CCS were general worries or uncertainty, followed by the perception of powerlessness, annoyance, and aversion. However, respondents also stated a feeling of calmness regarding CO_2 storage.

2.4. Questions addressed and logic of empirical procedure

Whereas previous qualitative research has had laypeople evaluate CCU against the background of CCS as a side aspect of investigating perceptions of CCU, studies with a main focus on directly comparing and quantifying perceptions of CCU and its sister technology CCS are rare (Arning et al. [63]). It has been suggested that a commingling of CCS and CCU in laypeople's minds might lead to misconceptions about CCU [40]. By this, possibly a transfer of the negative public acceptance of CCS on CCU takes place (if, for example, CCU is understood as a way to promote the roll-out of CCS).

The knowledge how laypeople evaluate CCU technologies relatively to the CCS concept and the understanding whether they distinguish between the two technological approaches might be crucial for the successful implementation of novel CCU technologies. It is also vital to determine the critical parameters that can enable or hamper the roll-out of CCU. Therefore, our research aim was to comparatively study the general (socio-political) acceptance of CCS and CCU and to unveil if the same parameters are acceptance-relevant in the CCS and CCU context.

Our research questions were:

1) Which attitudinal characteristics (affective responses and beliefs) are associated with CCS and CCU? (RQ1)
2) Which impact do attitudinal characteristics (affective responses and beliefs) have on the general acceptance of CCS and CCU? (RQ2)
3) Do supporters and opponents of CCS also differ in their evaluations of CCU? (RQ3)

3. Material and methods

To answer the research questions (Section 2.4), an online survey was conducted in Germany in 2017 to examine CCS and CCU acceptance and to investigate the role that affective responses and beliefs play in the formation of acceptance. A quantitative country-wide approach was chosen to validate qualitative insights from a qualitative pre-study, in which relevant spontaneous associations regarding both technologies were collected. In the pre-study, two semi-structured brainstorming sessions were conducted with laypeople (n = 6) and experts in the field of CCS and CCU (n = 5): While laypeople were asked what they initially thought about the CCS and CCU technology and which spontaneous associations they had with each technology, experts were asked about benefits and barriers of CCS and CCU that might affect the public acceptance of both technologies.

The pre-study sample was recruited by announcement in the newspaper (searching for experts and laypeople in the context of renewable energy technologies (CCS)). Participation was not rewarded. The sample consisted of five women and six men between 20 and 57 years (M = 35.6 years, SD = 14.3). Outcomes of the pre-study (primarily from the brainstorming with laypeople) were used to derive the affective/cognitive evaluation dimensions and adjective pairs, respectively.

In the following section, the structure of the questionnaire, the sample, and the procedure of data analysis are outlined.

3.1. Questionnaire

Questionnaire items were based on the current knowledge about critical acceptance parameters in renewable energy technologies and on the work of Huijts et al. [18].

At the beginning of the questionnaire, respondents were introduced to the technological concepts of CCS and CCU by briefly explaining the different process routes of CCS and CCU (for CCU, the production of plastic products and fuels was taken as an application example). Detailed information about the process steps and the different ecological motivations of CCS and CCU followed later in the specific questionnaire parts on CCS and CCU perceptions (questionnaire parts 3 and 4).

In the second part of the questionnaire, participants were surveyed for demographic and attitudinal variables. For demographic data, age, gender, and education were assessed. As attitudinal variables (see Table 1), we included environmentally aware behavior (measured using 4 items from European Commission [64] and Wippermann et al. [65]), technical self-efficacy (four items from Beier [66]), and self-assessed knowledge about CCS and CCU (five items on different process steps of CCS and CCU: CO_2 capture, transport, storage, utilization, and plastic products made partly from CO_2). Also, the personal innovativeness, i.e., a person's interest in and willingness to adopt innovative technologies, was measured by four items from Fazel [67]. Furthermore, an assessment of participants' risk orientation (a person's general attitude towards risk and safety) was included using four items from Rohrmann [68]. All attitudinal variables were measured on six-point Likert scales (min = 1, max = 6).

The third and fourth part addressed attitudes to and acceptance of CCS and CCU. CCS and CCU perceptions were investigated in a dependent design, i.e., every respondent had to evaluate both

Table 1
Overview of items used to measure attitudinal variables and item analysis statistics (Cronbach's α).

Attitudinal variable	Items	Cronbach's α
Environmentally aware behavior (European Commission [64], Wippermann et al. [65])	To protect the environment… ● when buying household appliances, I pay attention to a low energy consumption. ● I try to avoid waste caused by unnecessary packaging, unnecessary plastic bags, etc. ● I purposefully buy products that cause as little harm as possible to the environment both during their production and use. ● when buying textiles, I pay attention that they do not contain any harmful substances.	.82
Technical self-efficacy (Beier [66])	● I can solve many of the technical problems I am confronted with on my own. ● I really enjoy solving technical problems. ● Because I could cope well with technical problems so far, I am optimistic about future technical problems. ● I feel so helpless when interacting with technical devices that I rather keep my hands off them.	.88
Self-assessed knowledge about CCS and CCU	● I feel well-informed about CO_2 capture. ● I feel well-informed about CO_2 transport. ● I feel well-informed about CO_2 storage (CCS). ● I feel well-informed about CO_2 utilization (CCU). ● I feel well-informed about the utilization of CO_2 as feedstock for the manufacturing of plastic products.	.97
Personal innovativeness (Fazel [67])	● I regularly look out for new products. ● I often search for information about new technologies and products that could be of interest to me. ● Most often, I am the first of my friends to test new products. ● I find it interesting to test new products.	.89
Risk orientation (Rohrmann [68])	● I'm quite cautious when I make plans and when I act on them. ● I follow the motto, 'nothing ventured, nothing gained'. ● I've not much sympathy for adventurous decisions. ● I like to put something at stake.	.76

All attitudinal variables were measured on six-point Likert scales (min = 1, max = 6).

Table 2
Adjective pairs used in the semantic differential scale, overlying dimensions, and item analysis statistics (Cronbach's α).

Dimension	Cronbach's α	Negative adjective	Positive adjective
Acceptance	–	unacceptable	acceptable
Benefits	CCS: α=.94 CCU: α= .96	useless futile	useful makes sense
Risks	CCS: α= .95 CCU: α= .96	dangerous risky	harmless risk-free
Technological evaluation	CCS: α= .66[a] CCU: α= .70	immature conventional	mature innovative
Ecological evaluation	CCS: α=.85 CCU: α= .88	short-lived pollutive	sustainable ecofriendly

[a] Although the technological dimension reached a comparably lower alpha for CCS, it was maintained to allow for a direct comparability with the other dimensions.

technologies one after the other (randomized order). This design was chosen to obtain evaluations of both technologies – in a single frame of reference – by the same respondents to account for an individual response bias and allow for a direct comparison of both technologies. Furthermore, this procedure allowed for investigating possible differences in CCU perceptions by CCS supporters and opponents.

To assess affective responses and beliefs, identifying hidden barriers and drivers for a technology [57], the semantic differential technique was used (Osgood et al. [69]). Respondents were asked to rate both technologies on a semantic differential scale consisting of nine bipolar adjective pairs referring to general benefit and barrier dimensions, technological and ecological evaluations (Table 2). The adjectival scales were developed based on Zaunbrecher et al. [57] and results from brainstorming sessions on CCS and CCU associations conducted prior to the present study, in which spontaneous impressions of CCS and CCU were investigated.

Each pair of adjectives was evaluated on a ten-point scale with the scale poles representing the positive (= 10) and negative (= 1) adjectives (e.g., for the polarized adjectives "useful-useless", scale point 1 corresponded to "useless", whereas scale point 10 signified "useful").[2]

Bearing in mind that the two technological concepts should be treated individually to avoid a commingling of CCS and CCU [40], the sequence of the questionnaire parts on CCS and CCU as well as the order of the adjectival scales within the semantic differential were randomized to prevent sequence effects, e.g., a spillover of a negative attitude on CCS on the evaluation of CCU or vice versa. Moreover, the questionnaire instructions were developed together with CCS/CCU experts to explain the technologies under study intelligibly and in a technically accurate manner. Here, special attention was paid to the different ecological motivation of CCU compared to CCS: It was pointed out that CCU is less about the reduction of CO_2 emissions and more about saving fossil resources used in the manufacturing of products because the global CO_2 demand for the manufacturing of CO_2-based products is considerably lower than the carbon dioxide emissions annually produced worldwide.

Prior to the online survey, the questionnaire was pre-tested to check for the comprehensibility of the instruction and the questionnaire items as well as to exclude possible adjective pairs that pre-testers reported not to associate with CCS and CCU.

3.2. Sample and user characteristics

Survey data have been collected in 2017 (summer) via an online panel of an independent market research company to cover a census representative sample (age, gender, education). Respondents were financially rewarded for their participation in accordance with German wage standards. 636 respondents from all regions of Germany participated in the study. After exclusion of incomplete data sets, speeders (all participants whose response time was below 35% of the median), and internally inconsistent answering patterns, 449 data sets were accepted

[2] Note that we deliberatively dismissed costs as an additional acceptance factor, even though it is known from previous research that costs are highly acceptance-relevant (e.g., Huijts et al. [18]). However, as – especially in innovative products which are not yet on the market – ideas of participants about the adequacy of costs is not yet established, we decided to postpone this factor on future work.

for further analysis. Respondents, 47.7% males and 52.3% women, were between 24 and 80 years old ($M = 50.2$ years, $SD = 12.2$). 25.4% of the sample stated to hold a university degree or higher, 26.7% had finished vocational training, and 13.8% held a university entrance certificate as highest educational attainment. Moreover, 21.6% reported to have a general certificate of secondary education, while 11.6% had a lower secondary school qualification. 0.4% each stated to have another or no educational attainment.

The sample evaluated their daily behavior as rather environmentally aware ($M = 4.45$, $SD = 0.93$). Self-assessments of technical self-efficacy ($M = 3.58$, $SD = 0.66$) and personal innovativeness ($M = 3.61$, $SD = 1.18$) were on a medium level, indicating a rather neutral attitude towards technology. In comparison, self-assessed knowledge about CCS and CCU technologies was low ($M = 2.63$, SD = 1.25). Furthermore, participants reported a rather low general willingness to take risks ($M = 2.89$, $SD = 0.93$), meaning respondents were on average more oriented towards safety than towards running risks.

3.3. Data analysis

Mean scores for all scales with multiple item-measurement were calculated. Data was analyzed by applying descriptive and inference statistics. First, mean values for each of the nine adjectival scales of the semantic differential were calculated for CCS and CCU. A repeated–measures analysis of variance (ANOVA) was performed to compare means for CCS and CCU. To examine the underlying factor structure, a principal component analysis with Varimax rotation was applied to the bipolar adjectival scales for CCS and CCU. The impact of affective responses and beliefs on the acceptance of CCS and CCU was investigated using stepwise regression analyses. In a last step, a group comparison was conducted between supporters (CCS acceptance score ≥7) and opponents of CCS (CCS acceptance score ≤4) using ANOVAs and regression analysis to detect possible differences in perceptions and acceptance-relevant parameters.

4. Results

4.1. Affective responses and beliefs associated with CCS and CCU (RQ1)

Results of semantic differential scaling for CCS and CCU are presented in Fig. 1. While acceptance of CCU was rather neutral ($M_{CCU} = 5.63$, $SD = 2.55$), CCS was rated significantly lower and slightly negatively ($M_{CCS} = 4.81$, $SD = 2.52$; $F(1{,}448) = 67.15$, $p < 0.001$, $\eta_p^2 = .13$). As Fig. 1 shows, CCS and CCU displayed a similar evaluation profile. For both technologies, innovativeness was the best-rated attribute ($M_{CCS} = 5.85$, $SD = 2.39$; $M_{CCU} = 6.38$, $SD = 2.40$). In contrast, the technological maturity of CCS and CCU was rated worst ($M_{CCS} = 4.02$, $SD = 2.36$; $M_{CCU} = 4.62$, $SD = 2.34$), followed by the adjectival scales "risky – risk-free" ($M_{CCS} = 4.15$, $SD = 2.33$; $M_{CCU} = 4.70$, $SD = 2.32$) and "dangerous – harmless" ($M_{CCS} = 4.31$, $SD = 2.38$; $M_{CCU} = 4.94$, $SD = 2.40$). This means, CCS and CCU were perceived as slightly risky.

Table 3
Results of ANOVAs for differences in affective responses and beliefs towards CCS and CCU (n = 449, min = 1, max = 10, df1 = 1, df2 = 448).

Bipolar adjectival scales	F	p	η_p^2
Immature – mature	66.46	< 0.001	.13
Useless – useful	35.50	< 0.001	.07
Futile – makes sense	59.28	< 0.001	.12
Dangerous – harmless	51.59	< 0.001	.10
Short-lived – sustainable	44.82	< 0.001	.09
Risky – risk-free	44.54	< 0.001	.09
Unacceptable – acceptable	67.15	< 0.001	.13
Conventional – innovative	44.02	< 0.001	.09
Pollutive – ecofriendly	44.03	< 0.001	.09

For CCS, mean values of all bipolar scales (except for innovativeness) were below the hypothetical midpoint of the scale and thus the technology characteristics were evaluated slightly to rather negatively. Compared to CCS, the profile line for CCU was closer to the midpoint of the scale. All differences between CCS and CCU were statistically significant ($p < 0.001$, see Table 3), meaning CCU was evaluated more positively on all evaluative dimensions. As can be seen from Fig. 1, CCU was perceived as (slightly to rather) immature, dangerous, risky, and pollutive but at the same time as useful, sensible, sustainable, and innovative. Thus, although some barriers were seen, benefits of the CCU technologies were as well acknowledged.

Next, a principal component analysis with Varimax rotation was applied to the bipolar adjectival scales for CCS and CCU. By this, it was examined if the underlying factor structure rather represented different technologies (CCS and CCU) or reflected the different evaluative dimensions (benefits, risks, technological and ecological aspects). This allows further insights into whether respondents made a nuanced assessment of the technologies taking different evaluative dimensions into account or whether they rather evaluated CCS and CCU as a whole. Table 4 shows the factor loadings of the (added together) 18 adjectival

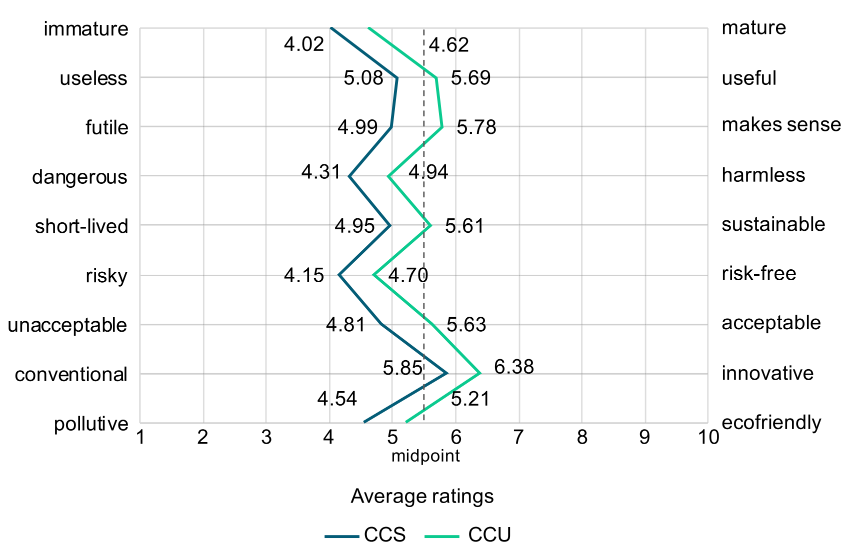

Fig. 1. Mean affective-cognitive evaluations of CCS and CCU (n = 449).

Table 4
Rotated factor loadings of affective responses and beliefs towards CCS and CCU on the extracted factors.

Bipolar adjectival scales	*CCU*	*CCS*	*Inno*
CCU unacceptable – acceptable	.836		
CCU dangerous – harmless	.824		
CCU risky – risk-free	.822		
CCU useless – useful	.814		
CCU futile – makes sense	.813		
CCU pollutive – ecofriendly	.804		
CCU immature – mature	.744		
CCU short-lived – sustainable	.732		
CCS dangerous – harmless		.851	
CCS risky – risk-free		.848	
CCS unacceptable – acceptable		.820	
CCS immature – mature		.790	
CCS pollutive - ecofriendly		.779	
CCS futile – makes sense		.764	
CCS useless – useful		.747	
CCS short-lived – sustainable		.713	
CCS conventional – innovative			.768
CCU conventional – innovative			.693

Bartlett's test of sphericity $p < 0.001$, KMO = .954, Inno: innovativeness.

scales for CCS and CCU.

As taken from Table 4, three factors were extracted. The obtained factor structure rather reflected a difference between technologies than a difference between evaluation criteria. The first factor referred to the CCU technology, while the second factor was related to the CCS technology. The third factor contained the two items on innovativeness for CCS and CCU and can therefore be referred to as "innovativeness factor". Together the extracted factors explained 85.0% of the total variance.

4.2. Impact of affective responses and beliefs on the acceptance of CCS and CCU (RQ2)

To examine the impact of affective responses and beliefs on the acceptance of CCS and CCU, the bipolar adjectival scales were subsumed under the overlying dimensions benefits, risks, technical and environmental characteristics (see Table 2). Then, the four dimensions were entered as independent variables into stepwise regression analyses, while CCS and CCU acceptance were entered as dependent variables. The resulting regression models for CCS and CCU are reported in Fig. 2.

In the CCS acceptance model, the technological dimension was excluded from the model, meaning it had no significant impact. The benefit, risk and ecological dimensions explained together 86.3% of variance in CCS acceptance ($F(3,445) = 937.73$, $p < 0.001$) with benefits having the strongest impact, followed by risks and ecological aspects (see Fig. 2). Note that a high score on the risk dimension corresponds to a low risk (a high value on the corresponding adjectival scales means that ratings were closer to the scale poles "risk-free" and "harmless"). That means, a higher benefit perception, a lower perceived risk, and a positive ecological evaluation tended to increase CCS acceptance. By contrast, the regression model for CCU acceptance included in addition to the benefit and risk dimension also the technology dimension (see Fig. 2), whereas ecological aspects were discarded. The resulting regression model accounted for 88.7% of variance in CCU acceptance ($F(3,445) = 1169.25$, $p < 0.001$). Again, a higher benefit perception and lower risk perception were related to a higher acceptance – as was a more positive evaluation of technological aspects.

4.3. Comparing affective responses and beliefs for supporters and opponents of CCS (RQ3)

In a next step, it was investigated whether respondents who were in favor of CCS also supported CCU technologies and whether rejection of CCS also meant having a critical attitude towards CCU. Therefore, the sample was divided into two groups: "supporters" and "opponents" of CCS. Participants with a score between 1 and 4 on the adjectival scale "unacceptable – acceptable" for CCS acceptance were sorted into the group of *opponents*, while respondents with a score between 7 and 10 were classified as *supporters* of CCS. Data sets with a rather neutral rating for CCS acceptance (score between 5 and 6; n = 128, which corresponds to 28.5% of the sample) were excluded from the analysis to create more variance between the groups.

First, user profiles of *CCS supporters* and *opponents* were analyzed to detect possible differences. Results are shown in Table 5.

In the group of *supporters*, there was a significantly higher share of male participants compared to the group of *opponents*. Furthermore, *CCS supporters* were generally more willing to take risks and they reported significantly more positive attitudes towards technology in comparison to *CCS opponents*: *Supporters* had a higher technical self-efficacy, personal innovativeness, and self-reported knowledge about CCS and CCU.

Afterwards, affective responses and beliefs were compared for *CCS supporters* and *opponents* to tackle the question if CCS and CCU perceptions are similar or if they entail technology-specific differences. As Fig. 3 shows, *supporters* of CCS evaluated CCU on a similarly positive level as CCS. For both technologies, scores on all evaluative dimensions were above the hypothetical midpoint of the scale indicating a positive overall response. There were no statistically significant differences

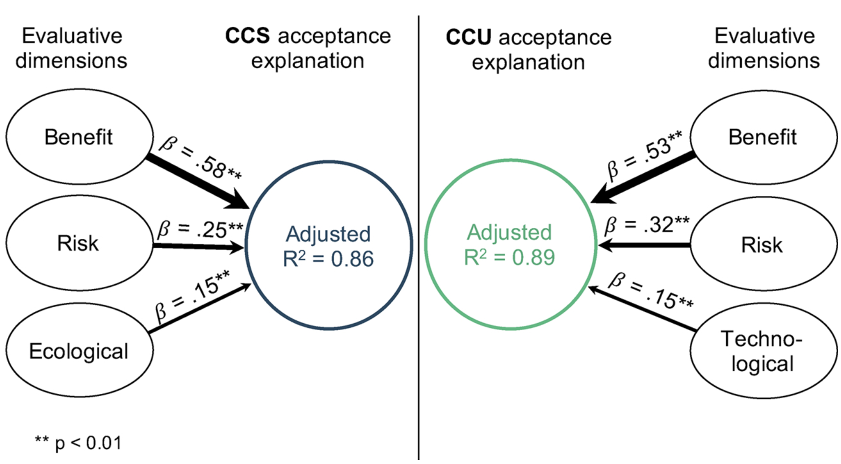

Fig. 2. Regression models for the impact of affective responses and beliefs on CCS and CCU acceptance (n = 449). Note that a high score on the risk dimension corresponds to a low risk.

Table 5
User profiles for *supporters* and *opponents* of CCS.

	CCS opponents (n = 198)	CCS supporters (n = 123)	Significance Testing (MANOVA)
Age	*M* = 50.6 years, *SD* = 11.1	*M* = 51.0 years, *SD* = 13.3	p = n.s.
Gender	44.4% male, 55.6% female	59.3% male, 40.7% female	$\chi^2(1) = 6.74$[a], $p < 0.01$
Technical self-efficacy	*M* = 3.50, *SD* = 0.68	*M* = 3.74, *SD* = 0.64	$F(1,319) = 10.29$, $p < 0.01$, $\eta_p^2 = .03$
Personal innovativeness	*M* = 3.38, *SD* = 1.19	*M* = 3.99, *SD* = 1.14	$F(1,319) = 20.50$, $p < 0.001$, $\eta_p^2 = .06$
Self-assessed knowledge	*M* = 2.44, *SD* = 1.15	*M* = 3.14, *SD* = 1.33	$F(1,319) = 24.44$, $p < 0.001$, $\eta_p^2 = .07$
Environmentally aware behavior	*M* = 4.43, *SD* = 0.96	*M* = 4.62, *SD* = 0.92	p = n.s.
Risk orientation	*M* = 2.80, *SD* = 0.92	*M* = 3.13, *SD* = 1.01	$F(1,319) = 9.23$, $p < 0.01$, $\eta_p^2 = .03$

[a] As gender is a nominal variable, a Chi Square test was performed.

Table 6
Results of ANOVAs for differences in affective responses and beliefs towards CCS and CCU by *CCS opponents* (n = 198, min = 1, max = 10, df1 = 1, df2 = 197).

Bipolar adjectival scales	F	p	η_p^2
Immature – mature	61.11	< 0.001	.24
Useless – useful	38.79	< 0.001	.17
Futile – makes sense	68.90	< 0.001	.26
Dangerous – harmless	48.95	< 0.001	.20
Short-lived – sustainable	43.25	< 0.001	.18
Risky – risk-free	58.45	< 0.001	.23
Unacceptable – acceptable	97.72	< 0.001	.33
Conventional – innovative	30.48	< 0.001	.13
Pollutive – ecofriendly	57.78	< 0.001	.23

between *CCS supporters'* evaluations of CCS and CCU, except for the adjectival scales "dangerous – harmless" ($F(1,122) = 6.21$, $p < 0.05$, $\eta_p^2 = .05$) and "conventional – innovative" ($F(1,122) = 8.41$, $p < 0.01$, $\eta_p^2 = .07$). Respondents who were *in support of CCS* perceived CCU technologies as even less dangerous and more innovative (see Fig. 3).

However, the group of *CCS opponents* rated CCU overall significantly better compared to CCS: All differences between CCS and CCU were statistically significant (Table 6) although the evaluation profile had a similar shape for CCS and CCU. Nevertheless, CCU was still evaluated rather negatively by *CCS opponents* as mean values for all adjectival scales were below the midpoint of the scale (Fig. 3).

Strikingly, independently of groups (*supporters* and *opponents*), innovativeness of CCS and CCU was the best-rated characteristic. Apparently, both technologies were rather perceived as novel, innovative approaches, which could possibly be a driver for acceptance. On the other hand, technological maturity and risk evaluations of CCS and CCU were the worst-rated evaluative dimensions in both acceptance groups. Thus, although absolute scores differed between the two groups, members of both groups saw the same relative strengths and weaknesses for CCS and CCU.

Moreover, results from a MANOVA (Table 7) revealed that *CCS opponents* and *supporters* differed not only in terms of CCS acceptance but in their assessments of all bipolar adjectival scales for CCS ($F(9,311) = 201.12$, $p < 0.001$, $\eta_p^2 = .85$) and CCU ($F(9,311) = 29.86$, $p < 0.001$, $\eta_p^2 = .46$). This shows that differing attitudes towards CCS go hand in hand with differences in perceptions of CCU: People with a negative view on CCS were overall more critical of CCU than participants who were supportive of CCS. Therefore, CCS opponents might also be critical towards the implementation of CCU technologies in Germany.

4.4. Impact of affective responses and beliefs on acceptance for CCS supporters and opponents (RQ3)

To test whether acceptance-relevant affective responses and beliefs differed for *supporters* and *opponents* of CCS, stepwise regression procedures were run for both groups. The overlying dimensions perceived benefits, perceived risks, technological and ecological evaluations were entered as independent variables and CCS and CCU acceptance as outcome variables. The regression models explaining CCS acceptance

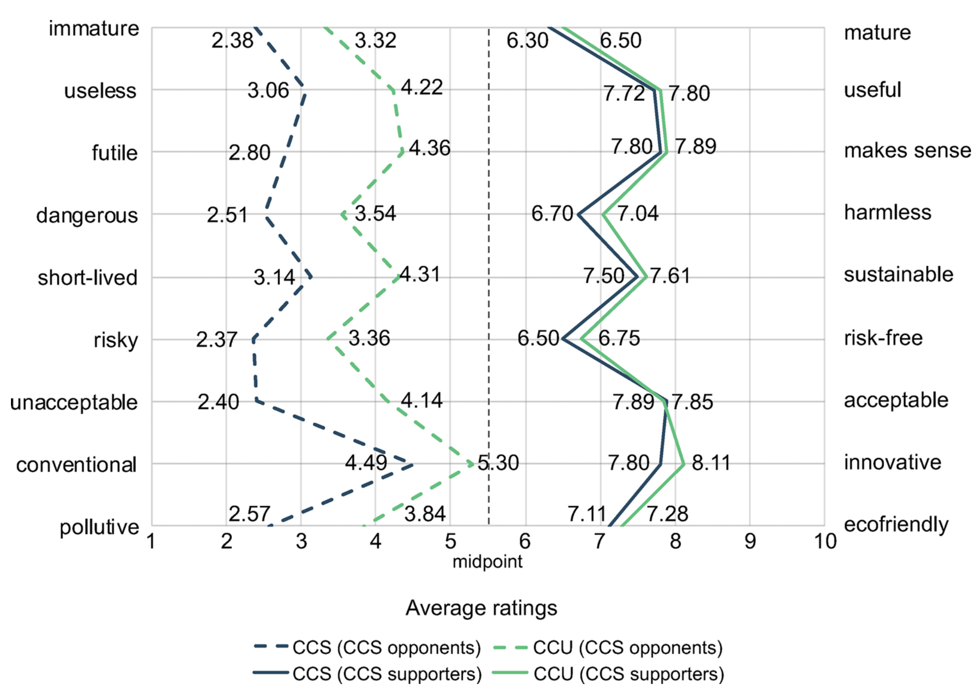

Fig. 3. Mean affective-cognitive evaluations of CCS and CCU for *CCS supporters* (n = 123) and *opponents* (n = 198).

Table 7
Results of MANOVAs for differences in affective responses and beliefs between *CCS supporters* (n = 123) and *opponents* (n = 198, min = 1, max = 10, df1 = 1, df2 = 319).

Bipolar adjectival scales	Affective responses and beliefs towards CCS			Affective responses and beliefs towards CCU		
	F	*p*	η_p^2	*F*	*p*	η_p^2
Immature – mature	412.27	< 0.001	.56	193.03	< 0.001	.38
Useless – useful	588.72	< 0.001	.65	188.77	< 0.001	.37
Futile – makes sense	728.77	< 0.001	.70	178.64	< 0.001	.36
Dangerous – harmless	463.99	< 0.001	.59	229.15	< 0.001	.42
Short-lived – sustainable	428.27	< 0.001	.57	177.26	< 0.001	.36
Risky – risk-free	512.84	< 0.001	.62	230.43	< 0.001	.42
Unacceptable – acceptable	–	–	–	213.95	< 0.001	.40
Conventional – innovative	187.41	< 0.001	.37	121.93	< 0.001	.28
Pollutive – ecofriendly	578.89	< 0.001	.65	197.16	< 0.001	.38

Note that results for "unacceptable-acceptable" are not reported for CCS because group splitting was done on the basis of this variable.

for the two groups are displayed in Fig. 4.

In the group of *CCS supporters*, affective responses and beliefs towards CCS explained 52.5% of variance in CCS acceptance ($F(2,120) = 68.39$, $p < 0.001$): Perceived benefits were the strongest promoter of acceptance, followed by the risk dimension (see Fig. 4), whereas the technological and ecological dimension had no significant impact and were excluded from the model.

For *CCS opponents*, affective responses and beliefs had a comparably higher explanatory power: The model accounted for 63.7% of variance in CCS acceptance ($F(3,194) = 116.08$, $p < 0.001$). In addition to the benefit and risk dimensions, which contributed almost equally to CCS acceptance, also technological aspects played a role (see Fig. 4). More favorable evaluations on all three dimensions tended to increase CCS acceptance in the group of *opponents*.

Similar to the CCS context, for *CCS supporters* (Fig. 5) the acceptance of CCU was solely affected by perceived benefits and the risk dimension. Again, benefits had the strongest positive impact: the higher perceived benefits and perceived harmlessness of CCU, the more favorable was acceptance. Compared to CCS, the predictive power of the regression model was higher as it explained 79.2% of variance in CCU acceptance ($F(2,120) = 233.97$, $p < 0.001$).

For *CCS opponents*, affective responses and beliefs explained with 85.4% an even higher proportion of CCU acceptance ($F(3,194) = 385.90$, $p < 0.001$). The regression model for the group of *opponents* (also displayed in Fig. 5) included the benefit, risk, and technological dimensions (as it had already been the case for CCS acceptance). Again, positive evaluations on the three dimensions were related to a higher acceptance of CCU. But in contrast to the CCS context, for *CCS opponents* perceived benefits had a noticeably stronger effect on CCU acceptance than the risk dimension and the impact of technological aspects was increased (see Fig. 5).

5. Discussion

In the following, the findings are discussed and recommendations for information and communication strategies for CCS and CCU projects are derived. The section closes with an overview of methodological limitations and future research duties.

5.1. Affective responses and beliefs towards CCS and CCU and their impact on acceptance (RQ1/2)

Comparing affective responses to and beliefs of CCS and CCU, basically, a similar evaluation pattern was uncovered: For both technologies, the best-rated characteristic was their perceived innovativeness and the worst-rated characteristic their lack of technological maturity. This could be a hint that respondents perceived an inverse relationship between innovativeness and maturity: Possibly, they believed that a novel, innovative technology with a low public awareness and a short implementation history could not be technologically mature (e.g., because of a lack of long-term experience). Technological maturity issues have also been identified in other studies on CCS acceptance and caused concerns of unknown and unforeseen risks [19,35]. Besides technological maturity, in the present study also riskiness and hazardousness were among the worst-evaluated characteristics for CCS and CCU but, overall, both technologies were only perceived to be slightly to rather

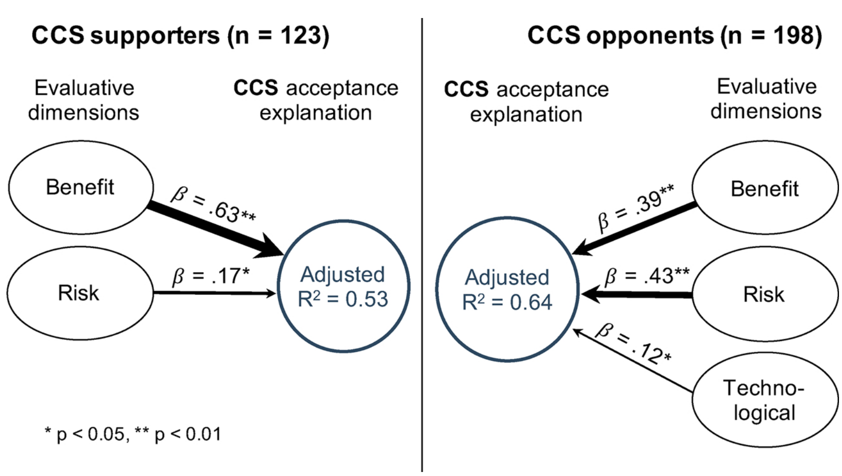

Fig. 4. Regression models for the impact of affective responses and beliefs on CCS acceptance for *CCS supporters* (n = 123) and *opponents* (n = 198).

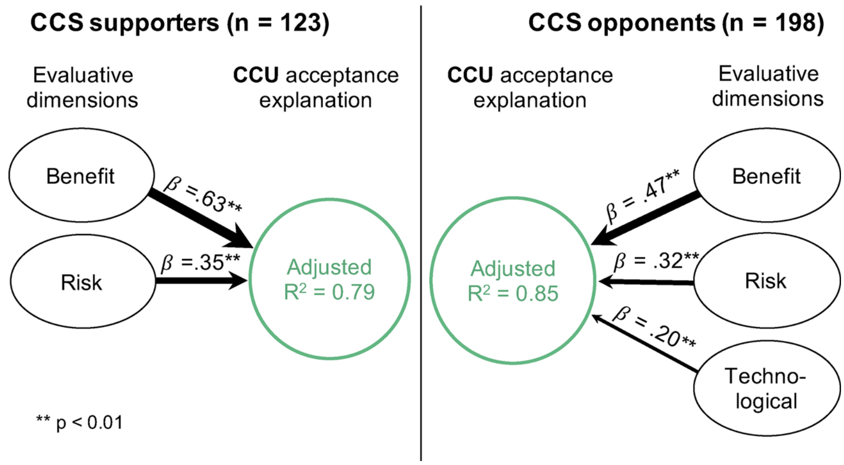

Fig. 5. Regression models for the impact of affective responses and beliefs on CCU acceptance for *CCS supporters* (n = 123) and *opponents* (n = 198).

risky. The rather low level of risk perception mirrors findings from recent studies on CCU technology and product acceptance (e.g., [27]).

Overall, attitudes towards CCS were on all dimensions significantly more negative than evaluations of CCU. Whereas CCS was rated negatively on every characteristic except for innovativeness, CCU was seen in a more differentiated way. Negative evaluations of CCU were related to technological immaturity, riskiness, hazardousness, and ecological harmfulness, while usefulness, sustainability, and innovativeness were seen positively and the CCU technology was believed "to make sense" in the context of the renewable energy transition. The overall positive evaluation of CCU benefits confirms recent findings in which CCU technologies and products were evaluated as rather useful and beneficial [27].

Underlining the importance of innovativeness as characteristic feature of CCS and CCU technologies, the conducted principal component analysis of affective responses and beliefs towards CCS and CCU identified innovativeness as only evaluation-related factor. The other two relevant factors (one CCS and one CCU factor) rather reflected a difference between the two technologies. This suggests that within the scope of the considered evaluation criteria – except for innovativeness – CCS and CCU were rated rather as a whole than making a differentiated assessment of different evaluation dimensions. The similar evaluation profile and the technology-related factor structure could be due to the low awareness of both technologies in our sample: Although respondents made a "felt" or "intuitive" difference between CCS and CCU (as CCU was rated significantly better than CCS), this difference could not be attributed to specific characteristics but was perceived overall. It is important to bear in mind that this does only apply for the characteristics included in the current study. Therefore, it cannot be ruled out that if other evaluation criteria were considered, respondents might have made a clearer distinction between CCS and CCU on these characteristics. In order to test whether the provision of additional information on CCS and CCU technologies leads to a more differentiated assessment and more distinct evaluation profiles, the study should be replicated with either respondents who are (or feel) more informed about CCS and CCU or by providing more technical information about CCS and CCU in the questionnaire instruction.

When examining the impact of affective responses and beliefs on CCS acceptance, both technology-specific and unspecific effects were detected. CCS and CCU acceptance was impacted by the general benefit dimension (CCS/CCU useful, makes sense) as strongest promoter of acceptance, followed by risk perceptions: The less risky and dangerous CCS and CCU technologies were perceived, the higher was acceptance, corroborating previous research on benefit and risk perceptions of CCS technologies and CCU products [25,27,34,48]. Reflecting a technology-specific difference, CCS acceptance was additionally found to be affected by ecological evaluations (CCS sustainable, ecofriendly), whereas evaluations of CCU were impacted by technological issues (CCU mature, innovative). Although CCU technologies are developed for ecological purposes and products are marketed accordingly, perceived technological maturity and innovativeness are more important for a socially accepted implementation of CCU technologies. Consequently, technological maturity issues might even be a greater barrier in the context of CCU than for CCS. This claim however is, strictly speaking, limited to the specific empirical procedure and the type and extent of information which was given to participants in this study. In this context, it should be further examined how public opinions can be reliably accessed (see Section 5.3). In line with the work of Upham and Roberts [36], a recent discussion [70] states that

> "if people in real-world settings form and express opinions about new technology based upon exposure to very limited information (e.g. short news articles), then the opinions derived from short focus-groups or questionnaires should not be too dissimilar to this" (p. 291).

This means that the comparably short information which was given to our participants resembles the real-world situation of laypeople reading short (newspaper) articles about novel technologies. Hence, taken from this, the measuring of laypeople's gut feelings and beliefs seems to be realistic (see more details in Section 5.3).

5.2. Perceptions of CCS and CCU by supporters and opponents of CCS (RQ3)

To arrive at a deeper understanding of similarities and differences between CCS and CCU perceptions, a group comparison was conducted between *supporters* and *opponents* of CCS. Although past research has identified acceptance issues for CCS projects [12–15] and suggests treating and discussing CCS and CCU individually to avoid a commingling of technologies [40], it was yet not understood whether people who reject CCS are also refusing of CCU technologies and if a positive attitude towards CCS goes in line with acceptance of CCU. The present findings revealed a similarly positive evaluation of CCU by *CCS supporters*, i.e., a positive attitude to CCS was found to be related to a favorable reception of CCU. On the other hand, *CCS opponents* were found to as well reject the CCU technology but to a lesser extent than CCS: Affective responses and beliefs towards CCU were significantly more favorable compared to CCS. This shows that participants made at least a small but distinct difference between the two technological approaches.

It was found that for *CCS supporters* the benefit dimension had a higher influence on CCS and CCU acceptance than for *CCS opponents*. For *CCS supporters*, perceived benefits were the strongest promoter of

acceptance, while in the *opponents* group the risk dimension contributed more equally to acceptance. This is a first hint that opposition and support are not composed in the same way: Support for CO_2-based technologies tends to be largely based on benefits associated with the technology. Compared to support, opposition seems to be guided by both, perceived advantages and negative outcomes, instead. An increased importance of perceived risks for aversion to energy technologies might explain why energy infrastructure projects often attract considerable opposition although citizens generally acknowledge the benefits linked to the technology. Therefore, future studies should examine this effect also for a wider selection of technologies.

5.3. The role of technical knowledge for assessing acceptance

In any study, in which public acceptance is explored with laypersons, the probability of capturing pseudo-opinions is a matter which needs discussion [71,72]. Pseudo-opinions can occur when laypersons – persons with a comparably low level of technical expertise – are asked to assess their preference for or against a specific technology. Due to their low knowledge, acceptance evaluations might have a low stability as the answers might reflect to a lesser extent acceptance-relevant attitudes, but rather temporary judgements triggered by the questions in the questionnaire. On the other hand, understanding public perceptions must include laypersons as important sources to capture the public attitudes in order to steer adequate information and communication strategies. Here, a sensitive tradeoff between the unwished bias of having random answers and the explicit goal of capturing the unbiased voice of the John Citizen has to be met. In this research, we took care for transparent instruction information which was given participants before the evaluations. The instruction material was carefully checked for technical correctness by technical experts and for a high understandability (by communication experts). Also, we had some pretest-participants which were asked to read and reproduce the instruction information. This way, we provided a solid information base for the assessment of the subsequent evaluations which should minimize the risk of pseudo-opinions.

Another methodological issue is the usage of rating scales to capture public perceptions. Basically, different opinions and argumentations can be found in the scientific community regarding the appropriate number of scale points in Likert scales. On the one hand, scales without a midpoint are proposed in order to prevent participants from relying only on a neutral position without deciding between more favorable or declining viewpoints. On the other hand, if respondents are truly indifferent or undecided towards the evaluation of a novel technology, a midpoint scale might better reflect these. The decision to use an even or uneven scale depends on the specific evaluation context and focus. In this study, in line with the argumentation of Moors [73] and Garland [74], we decided to use an even 10-point scale (without a midpoint but with enough categories so that respondents could allocate their responses to a number of options). Still, we cannot exclude any measurement inaccuracies around the missing midpoint. For the findings here, this methodological issue seems not to be relevant as both technologies were accessed by the same type of scale and therefore the differences assessed are reliable. For future research, however, it could be a valuable addendum to the current body of knowledge to replicate the study with a midpoint scale and a “don’t know” option in order to see how responses change, if at all.

From a social science perspective, the study of laypersons and their mental models about a technology [57,60] is a very insightful approach for communes, technical planners, science, and policy. The identification of laypeople’s information and knowledge gaps in line with deeply engrained risk perceptions [75–77] is not only a necessary pre-requisite for the development of effective communication strategies but is also instructive for technical planners to steer a participative technology development, in which the perspective of laypeople is considered.

5.4. Policy implications

The present findings can be used by involved stakeholders (e.g., governments, the CCS and CCU industry, and academic CCS and CCU research) for developing tailored communication strategies to inform the public about planned and operating CCS and CCU developments. By transparently informing citizens about CCS and CCU projects and adequately addressing laypeople’s requirements and concerns, the public awareness of CCS and CCU will be increased. This will help citizens to understand the two technologies, overcoming their prevailing misconceptions, and enable them to participate in the planning process (which is an important prerequisite for achieving a sustainable energy innovation [47]). A transparent and targeted information concept can thereby contribute to a deeper understanding of the multi-faceted issues involved in the planning process of CCS and CCU projects. In our study, perceived benefits were identified as the strongest promoter of acceptance for CCS and CCU (which was exemplified by the CO_2-based production of plastic products and fuels). Therefore, communication concepts to inform the public about CCS and CCU should address the ecological benefits of both technologies but point out the differences: that CCS is seen as a climate mitigation technology, while CCU (in the case of the CO_2-based production of plastic products and fuels) is regarded as an approach to reduce greenhouse gas emissions and fossil resource use but as more effective in saving fossil resources. Here, it is vital to consider that CCU does not denote a single technology but comprises numerous carbon utilization options that target at a wide range of different end products (such as chemicals, fuels, and minerals). Recent research corroborates that the diversity of end products is mirrored in the public perception of CCU products [78] and is steering different extents of trust and perceived fairness of the production process [79]. That means, the potential (and perceived) environmental and economic benefits differ depending on the considered CCU option (type of CO_2 source, applied capture technology, targeted end product, and the associated production process). Thus, communication concepts need to be tailored to the specific benefits that each CCU option holds. Overall, policy makers need to develop an awareness of addressing public perceptions in their public information, communication, and policy strategy.

Moreover, as perceived innovativeness was the best-rated feature of both technologies and technological maturity was evaluated worst, the innovative character of CCS and CCU should be explained to the public and at the same time an overview of the development state and test procedures for CCS and CCU technologies should be given. On the other hand, the perceived riskiness and hazardousness was revealed as hidden barrier for CCS and CCU acceptance – and was especially relevant in the group of *opponents*. Accordingly, communication concepts designed to inform the public about CCS and CCU projects, their goals, and their differences, should be open and transparent also with regard to possible risks of carbon capture, storage, and utilization. Equally important is that actors involved in the implementation of CCS and CCU technologies take public concerns and requirements seriously and address them appropriately instead of dismissing them as irrational fears and ignoring them [80].

Taking the potential of CO_2-utilization for reduction of CO_2 emissions and fossil resource use into account, future users should be involved as early as possible in the CCU product development process and should be informed transparently. Especially, it should be stressed that the CCU technology is less of a climate mitigation technology but a measure to reduce fossil resource depletion.

5.5. Future research duties

The applied study design and empirical methodology were suited to investigate the impact of affective responses and beliefs on CCS and CCU acceptance. Nevertheless, we identified some interesting aspects for future research.

5.5.1. Additional evaluation aspects

By predefining the evaluative dimensions in the questionnaire, we limited the evaluation within the given criteria. Still, more dimensions could be insightful to study the acceptance of CCU technologies in general and CCU products in particular. Yet, we did not cover potential financial costs as an evaluation dimension. This was done as the CCU products are currently only in the market entering stage and participants might not have a reliable idea of appropriate prices to get valid assessments. The integration of financial aspects is however an interesting factor for future research. On the one hand, it has been shown that the anticipation of additional costs for novel technologies can be a critical factor in terms of acceptance [45,81]. Also, compensation payments might decrease acceptance as participants feel that payments offered by companies might veil negative effects brought by technology [82]. On the other hand, the preceding brainstorming sessions revealed that – according to participants – high quality products would justify higher prizes. Future studies will therefore address the role of costs and compensation payments in the context of CCU technologies.

5.5.2. Sample issues

The sample used in this research was large and socio-demographically balanced and covered people from all over Germany. Therefore, outcomes can be referred to as prototypical, at least for Germany, but may be also insightful for questions of sustainable energy transition in other European countries. Still, since climate change and the development of renewable energy technologies are global challenges, future research should expand the perspective to other countries with different political targets and strategies to achieve a low-carbon economy, different CCS and CCU deployment histories, and different social and cultural value concepts. Especially, as culture has previously been identified as a factor impacting public perceptions of CCS [83].

5.5.3. The interdependence of affect and cognitions

From the vast psychological literature to emotions and cognitions it is known that individual mindsets and beliefs entail both, affective *and* cognitive components (e.g., [55,56]). Studies in the context of risk perceptions and energy acceptance also confirm the strong interplay of affects and cognitive beliefs [18,57–60]. In this study, we targeted affective responses and beliefs (mostly affective attributions and some of the attribution dimensions were more belief-based, e.g., 'mature', 'innovative', 'conventional'). The mélange out of affective and cognitive aspects in the evaluation dimensions used in this research does not weaken the outcomes as the differences between CCS and CCU can be seen in all adjectival pairs (in both the affective and the (assumed) affective-cognitive ones). A very recent study [59] shows how close emotional dimensions of renewable energy relate to cognitive or evaluative antecedents as for example novelty, certainty, goal significance, and coping potential, in line with the work of Moors [84]. Still, the transitions and the interplay between purely affective and more cognitive evaluation criteria in this field might be worth pursuing in future work, especially in combination with the study of appropriate information and communication strategies. Here it would be insightful to understand which of the underlying components, affective and/or cognitive should be addressed in order to raise acceptance for novel energy technologies.

5.5.4. Community acceptance

Finally, the current study exclusively focused on the socio-political acceptance of CCS and CCU technologies, neglecting community acceptance of specific projects and market acceptance of CCU products. Therefore, subsequent studies should also investigate the relevance of affective responses and beliefs for the local acceptance of CCS and CCU projects (e.g., as a part of a case study) and for the acceptance of and willingness to use CCU products in order to come to an understanding if the hidden drivers and barriers for CCS and CCU acceptance are the same across different dimensions of acceptance or if they are dimension-specific.

6. Conclusions

Acceptance of CCU was found to be positive and significantly higher than for CCS. Also, affective responses and beliefs towards CCU were significantly less negative compared to CCS. For both technologies, benefit perception had the strongest impact on acceptance, followed by perceived risks. Whereas CCS acceptance was affected by ecological evaluation criteria in addition, technological evaluations were more acceptance-relevant in the CCU context.

For the question whether CCS and CCU were evaluated similarly or differently, the present study revealed that – although CCU was rated significantly better than CCS – evaluation profiles of both technologies were structurally similar. Innovativeness was the best-rated characteristic and a perceived lack of technological maturity, riskiness, and danger were the highest barriers for both technologies. Opponents of CCS evaluated CCU technologies also negatively but significantly better compared to CCS. In turn, supporters of CCS rated CCU similarly favorable as CCS.

The findings inform tailored information and communication strategies for both CCS and CCU projects. Communication concepts should: 1) comprehensibly explain the ecological benefits of CCS and CCU and point out the differences between the two technological approaches, 2) explicate the innovative character of CCS and CCU, and 3) inform intelligibly and transparently about possible risks of carbon capture, storage, and utilization and address public concerns and requirements appropriately.

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